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No Evidence for [O III] Variability in Mrk 142

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ABSTRACT
Using archival data from the 2008 Lick AGN Monitoring Project, Zhang & Feng (2016) claimed to find evidence for flux variations in the narrow [O III] emission of the Seyfert 1 galaxy Mrk 142 over a two-month time span. If correct, this would imply a surprisingly compact size for the narrow-line region. We show that the claimed [O III] variations are merely the result of random errors in the overall flux calibration of the spectra. The data do not provide any support for the hypothesis that the [O III] flux was variable during the 2008 monitoring period.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – techniques: spectroscopic

1 INTRODUCTION

The method of reverberation mapping (Blandford & McKee 1982) uses the time delay between continuum variations in an active galactic nucleus (AGN) and the corresponding variations in the flux of broad emission lines to measure the size and structure of the broad-line region (BLR). In nearby Seyfert 1 galaxies and low-redshift quasars, the radius of the BLR measured via reverberation mapping typically ranges from a few light-days to a few light-months (Kaspi et al. 2000; Peterson et al. 2004; Bentz et al. 2009). Accurate measurement of reverberation lags requires monitoring campaigns with a cadence sufficient to resolve the flux variations, and with a total duration at least a few times greater than the lag time and preferably much longer.

The narrow-line region (NLR) in AGN spans a much larger radial range than the BLR. Narrow-band imaging and spectroscopic mapping indicate that the NLR often extends to ∼kpc scales in nearby Seyfert galaxies (e.g., Mulchaey et al. 1996; Schmitt et al. 2003; Bennert et al. 2006; Fischer et al. 2013), although some AGN such as NGC 5548 show evidence of a compact NLR core in which a significant fraction of the [O III] emission originates from scales of just tens of parsecs or less (Kraemer et al. 1998). Recent work has shown that the flux of the [O III] emission line in the well-studied AGN NGC 5548 does respond to long-term changes in continuum luminosity: over a $\sim$ 20-year span the [O III] emission in NGC 5548 faded by $\sim 20\%$ in response to a decrease in ionizing flux (Peterson et al. 2013). Based on this detection of narrow-line flux variability, Peterson et al. (2013) concluded that the majority of the [O III] emission originates from scales of $r \approx 1 - 3$ pc, a significantly smaller size than had previously been assumed. Further measurements of [O III] variations in additional AGN can potentially help to constrain the structure of the inner NLR on spatial scales too small to resolve directly.

Recently, Zhang & Feng (2016) claimed to find evidence for [O III] variability over a two-month timescale in the Seyfert 1 galaxy Mrk 142, using archival data from the 2008 Lick AGN Monitoring Project (LAMP2008; Bentz et al. 2009). They based this claim on correlations they found between the fluxes of the [O III] emission line and the AGN continuum in LAMP2008 spectra. If true, this result would be very surprising, as it would suggest that a substantial fraction of the NLR emission in Mrk 142 is generated on scales smaller than several light-weeks around the black hole. The purpose of this paper is to explain that the claimed detection of [O III] variability in Mrk 142 by Zhang & Feng (2016) is incorrect, as it is based on a misinterpretation of the data and a misunderstanding of the flux calibration procedures applied to the data. The LAMP2008 data do not reveal any evidence for [O III] variability.

2 FLUX CALIBRATION FOR REVERBERATION MAPPING CAMPAIGNS

We first review the flux calibration procedures applied to the LAMP2008 data. The spectra were acquired in Spring 2008 at Lick Observatory. Very few nights at Lick are photometric, and observing conditions ranged from thin cirrus to thick cloud cover. A flux standard star was observed on each night, and the AGN spectra observed on a given night were calibrated using the same night's standard star observations. This generally yields a good relative flux calibra-

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tion, in which the spectral shape is sufficiently reliable for reverberation mapping measurements. However, the overall normalization of the flux scale for each AGN spectrum is essentially random depending on the relative degree of cloud cover between the standard star observation and the AGN observations. Even for observations taken in truly photometric conditions, seeing variations and miscentering of the AGN in the spectrograph slit will cause some degree of spurious fluctuations in the broad-line and continuum fluxes measured on different nights. Thus, some rescaling of the data is required prior to carrying out measurements of emission-line or continuum light curves from the spectra.

To normalize the flux scales of the spectra to a consistent scale, we used the method described by van Groningen & Wanders (1992). This method is based on the assumption that the narrow emission-line fluxes remain constant over the timescale of an AGN reverberation mapping campaign (typically a few months), while the continuum and broad emission lines may be variable. A high-S/N reference spectrum is constructed, and each individual night's spectrum is scaled in a way that optimally matches the [O III] profile of the reference spectrum. The scaling method employs a linear wavelength shift, a multiplicative flux scaling factor, and convolution by a Gaussian kernel in order to fit the nightly [O III] profiles to the reference spectrum while allowing for variations in the AGN continuum flux underlying the emission line. The method does not specifically force each night's spectrum to have identical [O III] fluxes after scaling is applied; instead, it matches the nightly [O III] profiles to that of the reference spectrum as closely as possible, which leaves a small level of residual flux mismatch. van Groningen & Wanders (1992) stated that "errors in the calculated flux scaling factors are generally less than 5%, and for most cases much better."

This residual error can be determined by measuring the fractional variability amplitude ($f_{\rm var}$) in the [O III] light curve as measured from the scaled spectra, because any [O III] variability (over and above the amount expected from photon-counting uncertainties) can be attributed to calibration errors if the line flux is intrinsically constant. For a light curve with mean flux $\langle f\rangle$, variance σ_f^2, and rms measurement uncertainty δ, the fractional variability amplitude is

$$f_{\rm var} = \frac{\sqrt{\sigma_f^2 - \delta^2}}{\langle f\rangle}. \tag{1}$$

Thus, $f_{\rm var}^2$ is equivalent to the normalized excess variance in the light curve. As an example, for objects observed in the 2011 Lick AGN Monitoring Project, the values of $f_{\rm var}$ measured from the [O III] light curves after spectral scaling was applied ranged from 0.5% to 3.3% (Barth et al. 2015), consistent with the statement by van Groningen & Wanders (1992) that the flux scaling errors are often much better than 5%.

The LAMP2008 spectroscopic data are available in a public data release. This includes two versions of the spectra: the "final" reduced spectra before scaling is applied, and the scaled spectra after application of the van Groningen & Wanders (1992) method.

3 THE LAMP2008 MRK 142 DATASET

Our spectroscopic (Bentz et al. 2009) and photometric (Walsh et al. 2009) observations of Mrk 142 in Spring 2008 found a low level of intrinsic variability in this AGN. The spectroscopic monitoring duration was 68 days. Over this time span, the fractional variability amplitude $f_{\rm var}$ was just 2.4% for the V-band light curve and 8.6% for the broad Hβ line. Values of $f_{\rm var}$ below $\sim$ 10% correspond to fairly weak variability and are not often conducive to measurement of accurate reverberation lags, and Bentz et al. (2009) measured a rather uncertain lag of $\tau_{\rm cen} = 2.88^{+1.00}_{-1.01}$ days by cross-correlating the Hβ light curve against the V-band continuum. Bentz et al. (2013) present a further discussion of the LAMP2008 Mrk 142 dataset, noting that the $\sim$ 3-day lag is inconsistent with the BLR radius-luminosity relationship, suggesting that this lag value may be unreliable. More recently, Du et al. (2014) observed Mrk 142 during a period of stronger variability, and found $\tau_{\rm cen} = 6.4^{+0.8}_{-2.2}$ days.

Zhang & Feng (2016) used the archival LAMP2008 spectroscopic data to examine the relationship between [O III] and continuum variations in Mrk 142. From the outset, it is unlikely a priori that [O III] flux variations could be found over a two-month span, given the expectation that the NLR is extended on scales of at least a few light-years and possibly much larger. Additionally, the low level of intrinsic continuum variability in Mrk 142 during the 2008 monitoring period would be unlikely to lead to any detectable variations in narrow-line fluxes even if the NLR were very compact.

To search for [O III] variability, Zhang & Feng (2016) applied a spectral fitting procedure to decompose each night's spectrum into several emission-line and continuum components. The decomposition procedure was applied to both the unscaled and the scaled spectra. Then, light curves were measured for the AGN continuum, the broad Balmer lines, and the [O III] lines from the model components of both the unscaled and scaled spectra. They then examined correlations between the fluxes of different spectral components, in both the unscaled and scaled data.

Measuring correlations between the fluxes of different spectral components in the unscaled spectra conveys no useful information about the behavior of the AGN. As previously described, the overall flux scales of the nightly spectra are random, resulting from differences in cloud cover when the AGN and standard stars were observed. In fact, the greater the variations in cloud cover, the stronger the correlation that will be seen between the fluxes of different spectral components, since more variation in the nightly flux calibration will simply spread the (unscaled) fluxes out over a larger dynamic range. Using the unscaled spectra, Zhang & Feng (2016) plot correlations between the fluxes of Hα and Hβ, between Hα and the continuum, between [O III] and the continuum, and between [O III] and Hβ. In each case they find a strong correlation and they quote Spearman rank correlation coefficients. They specifically claim that the correlations in the unscaled spectra between [O III] flux and continuum flux, and between [O III] and Hβ, indicate that "there is reliable short-term [O III] variability over about two months." This claim has no merit whatsoever; these correlations are just the trivial result of night-to-night transparency variations.

Zhang & Feng (2016) also examine the correlations between fluxes of different spectral components in the scaled spectra. In each case they again find correlations, but these correlations are weaker than those seen in the unscaled spectra. The reason for this can be understood by considering the situation of an AGN that shows no intrinsic variability. For a non-variable AGN, the unscaled spectra will exhibit strong correlations between different spectral components due to differences in cloud cover from night to night. After applying the spectral scaling procedure, one might expect that the light curves would exhibit zero variability. However, due to the small residual scaling errors described previously, some small level of variations will be present in light curves measured from the scaled spectra. When applying the van Groningen & Wanders (1992) method, any errors in flux scaling will affect all spectral components equally, since each nightly spectrum is multiplied by an overall flux scaling factor. Thus, any residual errors in spectral scaling will naturally produce a detectable but spurious correlation between the fluxes of different spectral components.

For an AGN with low (but non-zero) intrinsic variability, these same considerations apply. When the residual flux scaling errors are similar to or larger than the true AGN variability amplitude, the light curves of different spectral components will be correlated, because the flux variations will be dominated by residual flux scaling errors. In the more favorable regime of strong AGN variability, when the spectral scaling method works well and residual flux scaling errors are small, then the [O III] flux would be expected to show little or no correlation with the variable continuum flux or broad Balmer-line fluxes.

In comparing the Hα vs. continuum flux correlation between the unscaled and scaled spectra of Mrk 142, Zhang & Feng (2016) find a stronger correlation to be present in the unscaled spectra. Instead of interpreting this as the result of clouds affecting the unscaled spectra and residual errors affecting the scaled spectra, they claim that "the spectral scaling method is not preferred, otherwise a stronger linear correlation could be expected from the scaled spectra." This is incorrect for a low-variability object such as Mrk 142 observed through highly variable clouds, a situation where the opposite outcome (a stronger correlation measured from the unscaled data) is expected. Similarly, Zhang & Feng (2016) claim that the correlation between Hα and Hβ fluxes should be stronger in the scaled than in the unscaled spectra "if the scaling calibration method were reasonable". This statement is based on the same incorrect reasoning. Again, the exact opposite conclusion should be reached for the case of an AGN with low intrinsic variability observed through highly variable cloud cover.

We can easily test whether the correlation between [O III] and continuum flux in the scaled spectra, as found by Zhang & Feng (2016), is caused by residual flux scaling errors. First, we display in Figure 1 the light curves of [O III] and the continuum, as listed in Table 1 of Zhang & Feng (2016). (Our own measurements are slightly different, but these small differences do not affect the outcome of our argument.) The plot confirms that the the AGN exhibited very low variability amplitude during this period in 2008. The continuum and [O III] light curves do not exhibit very strong features or long-term secular trends, which already disfavors the possibility that there might be a genuine physical correlation between the two. The flux variations appear

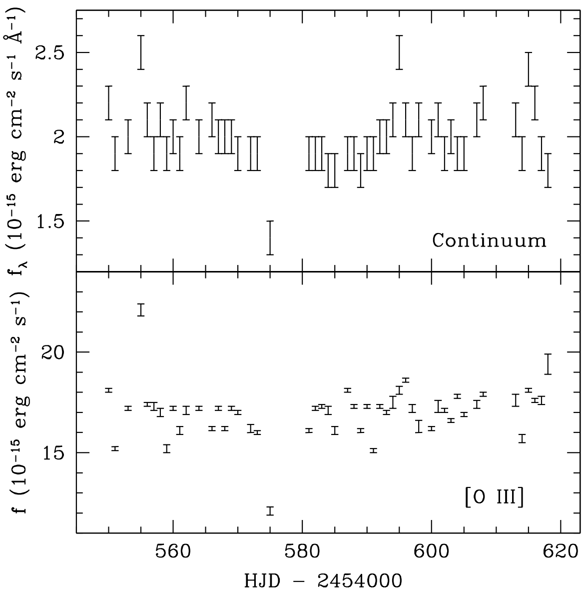

Figure 1. Light curves of the 5100 Å continuum (upper panel) and the [O III] line (lower panel). Data points are from the tables presented by Zhang & Feng (2016), which are based on their measurements from spectral decompositions of the LAMP scaled spectra. The apparent discreteness in the light curves is due to the fact that the data tables given by Zhang & Feng (2016) only list fluxes to one decimal place of precision (e.g., 2.2 ± 0.1). This rounding-off of data points does not affect any of the conclusions of this paper. There are two very noticeable outliers in the [O III] light curve, corresponding to particularly noisy spectroscopic observations. The corresponding points in the continuum light curve are clearly correlated outliers.

to be dominated by random scatter, a likely result of errors in spectral scaling.

The scatter in the [O III] light curve as measured from the scaled spectra is $f_{\rm var} = 7.6\%$, significantly worse than the average for recent reverberation mapping programs. However, a substantial contribution to this scatter comes from just two obvious outlier points in the data, at (HJD$-$2454000) = 4555 and 4575. These measurements correspond to spectroscopic observations having worse than average S/N, and can be easily recognized as spurious outliers. If these two points are discarded, $f_{\rm var}$ is reduced to 5.0%. Additionally, these same two dates appear as outliers in the continuum light curve. A scatter of 5% is still worse than typical, indicating that this was a somewhat problematic dataset (see also Bentz et al. 2013).

The presence of strongly correlated errors between the [O III] and continuum light curves is obvious from inspection of the light curves. The problem of correlated errors is well known in reverberation mapping studies. When emission-line and continuum fluxes are measured from the same spectra, cross-correlation often yields a spurious signal at zero lag as a result of the flux scaling errors affecting both light curves identically (Gaskell & Peterson 1987). In most recent reverberation-mapping campaigns (including LAMP2008), the AGN continuum light curve is measured from photometric data rather than from the spectroscopic data. This eliminates the problem of correlated errors between the continuum and emission line light curves, and also usually produces continuum light curves of higher quality.

We used the Interpolation Cross-Correlation Function (ICCF) method of Gaskell & Peterson (1987) to measure the lag between the [O III] and continuum light curves as measured from the scaled spectra. The results are displayed in Figure 2. The autocorrelation function (ACF) of the continuum light curve exhibits a narrow spike at zero lag. This is the typical signature of a light curve dominated by random noise rather than by genuine variability, since real AGN variability will produce a broader ACF indicating correlations over a broader range of timescales (e.g., Bentz et al. 2009). Similarly, the CCF measured between the [O III] and continuum light curves also exhibits a sharp peak at zero lag, and no significant signal corresponding to lags at any longer timescales. This is entirely consistent with expectations for a CCF dominated by correlated errors rather than by genuine AGN variability. If we remove the two epochs corresponding to the strong outliers in the [O III] light curve, the resulting CCF has the appearance of random noise, with a weak and noisy bump near zero lag and no evidence for a genuine lag at any positive lag time.

If the correlation between [O III] and continuum fluxes were real, the CCF would be expected to show evidence for some non-zero lag between the two light curves, with the lag time indicating the light-travel time between the continuum emitting region and the inner NLR. The observed CCF structure confirms that the correlations found by Zhang & Feng (2016) in the scaled spectra are not intrinsic to the AGN but instead are the result of correlated errors between spectral components. There is no evidence for genuine [O III] variations in this dataset.

Zhang & Feng (2016) also find a correlation between the [O III] line width and flux in the scaled spectra. This correlation can similarly be understood as a result of residual errors in the flux scaling method. The van Groningen & Wanders (1992) method applies a Gaussian kernel convolution to each night's spectrum to match the [O III] profiles to the reference spectrum, but the profile-matching is never perfectly realized and there are always residual differences in the night-to-night profiles. It is not at all surprising that a small spurious correlation might be introduced into the data by this method, in which broader widths for the [O III] profiles after scaling would correlate with higher fluxes.

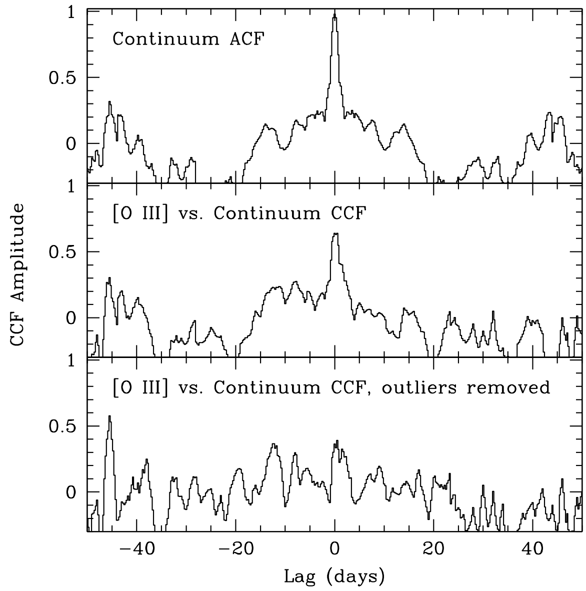

Figure 2. Autocorrelation function of the continuum light curve (top panel), cross-correlation of the [O III] light curve against the continuum (middle panel), and cross-correlation after removing the two outlier data points from the time series (lower panel). The narrow peak in the continuum ACF suggests that the continuum light curve is dominated by random errors rather than genuine AGN variability. The CCF is also dominated by a narrow spike at zero lag, the expected signature for a cross-correlation dominated by correlated flux calibration errors between the two light curves. After removing the two outlier data points from the light curves, there is no significant cross-correlation signal remaining.

4 DISCUSSION AND CONCLUSIONS

As we have shown, the Mrk 142 data from LAMP2008 are somewhat problematic in that the AGN variability is low and residual scaling errors are relatively large. This is a dataset that is intrinsically ill-suited to sensitive investigations of low-level AGN variability, and it is certainly not suitable for detection of narrow-emission line variations, which are expected on physical grounds to be extremely small on timescales as short as two months.

Searching for narrow-line variability in AGN remains an interesting problem, but the expected variability timescales would typically range from years to decades, corresponding to the light-travel time across the core of the NLR. Eracleous et al. (1995) estimated the *e*-folding time for decay of [O III] emission from a single cloud of density $n_{\rm H} = 500$ cm^{-3} to be ~ 4 years if the ionizing photon illumination of the cloud were turned off abruptly. Combined with the spatially extended size of the NLR, is is expected that short-term fluctuations in ionizing continuum luminosity would be largely washed away in the integrated response of the NLR. However, a long-duration secular increase or decrease in ionizing flux could produce a response in the [O III] line that might be suitable for crude reverberation mapping, as demonstrated the recent study of [O III] variations in NGC 5548 by Peterson et al. (2013). Narrow-line flux variations have also been found recently in some "changing-look" AGN in which the ionizing continuum luminosity changes dramatically, such as Mrk 590 (Denney et al. 2014) and Mrk 1494 (Barth et al. 2015).

It is worth considering whether it is even possible in principle to detect [O III] variations in a short-duration reverberation mapping program such as LAMP2008, given that very few nights during the campaign were photometric. Aside from the [O III] line, there is no other reference in the data that can be used to normalize the flux scales of the nightly spectra; [O III] is the only strong narrow line available. The starlight fraction will change from night to night as a result of seeing variations, and in any case starlight features are so weak as to be nearly undetectable in the Mrk 142 data. It would only be possible to test for [O III] variations if some other external calibration were available, such as a nearby nonvariable star consistently observed along the same long-slit as the AGN (e.g., Kaspi et al. 2000). We conclude that the LAMP2008 data do not have the capability to demonstrate the presence of [O III] flux variations at any variability amplitude that would be physically plausible.

The flux calibration issues related to the Mrk 142 dataset also motivate the question of whether improved spectral scaling methods can be developed that might provide better results than the van Groningen & Wanders (1992) scaling method. A new scaling algorithm was recently proposed by Li et al. (2014), and other new approaches should be explored. Improvements in spectral scaling methodology may become particularly relevant for new reverberation-mapping surveys using multi-fiber instruments to target large samples of AGN at higher redshift (Shen et al. 2015; King et al. 2015), because reliable flux calibration for fiber spectra can be much more difficult than for long-slit observations.

We have made the LAMP2008 spectroscopic data available in hopes that it will be of use for a variety of investigations.[1] We encourage researchers using these spectra to contact us with any questions regarding the data reductions or calibrations, so that future misunderstandings may be avoided.

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[1] The LAMP2008 spectroscopic data are currently available at `http://www.physics.uci.edu/~barth/lamp.html`.

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